Engineering Services Contract
Partnering To Engineer the Future

Resilience Emerging
from Scarcity and Abundance
American Society of Agronomy
Crop Science Society of America
Soil Science Society of America

Space Agriculture: Evolution of Plant Growth Technologies

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Air Revitalization Lab

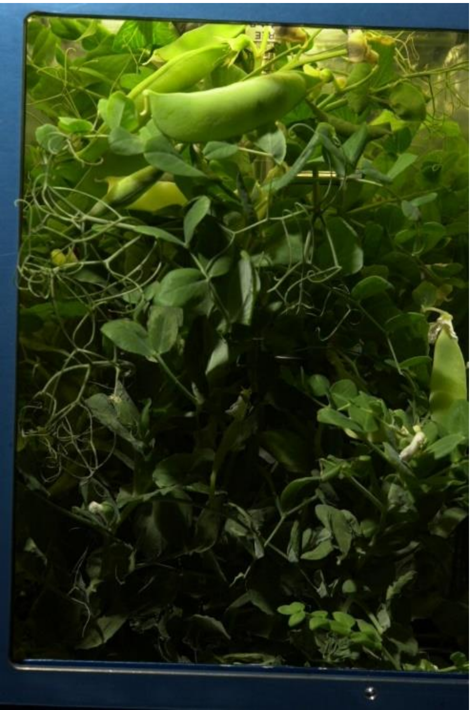
Kennedy Space Center, FL 32899

2016 Annual Meeting – Phoenix, AZ

In Space, explorers need *in situ* Food Production

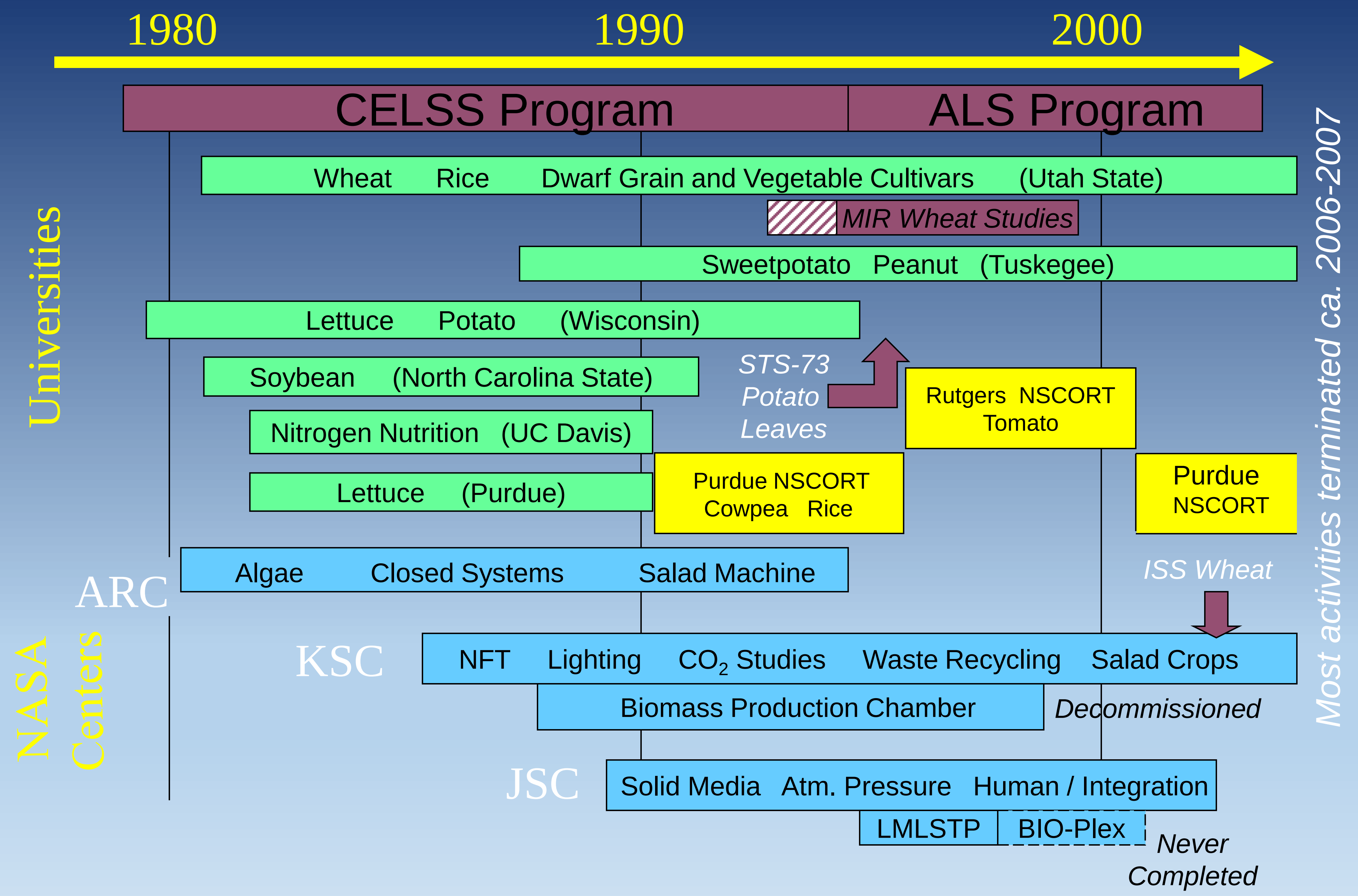
- Enables colonization of space
  - Sustainable: minimize logistics of resupply
  - Supplies: Light, CO_2, O_2, Nutrients, Water, Soil
  - Crew Psychological well-being: green Earth

LADA



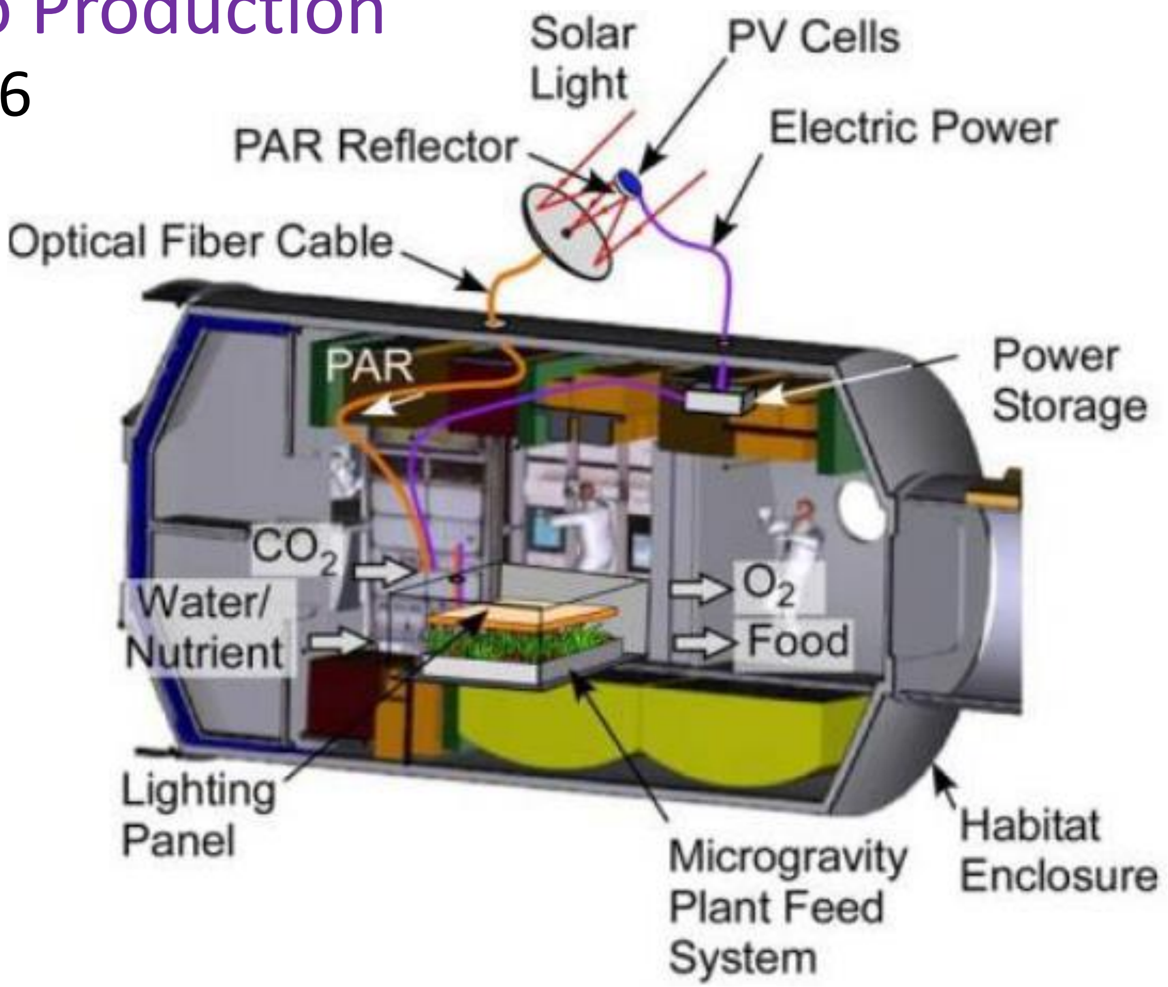
VEGGIE

NASA's Bioregenerative Life Support Testing



Salad Machine– Transit / Orbit

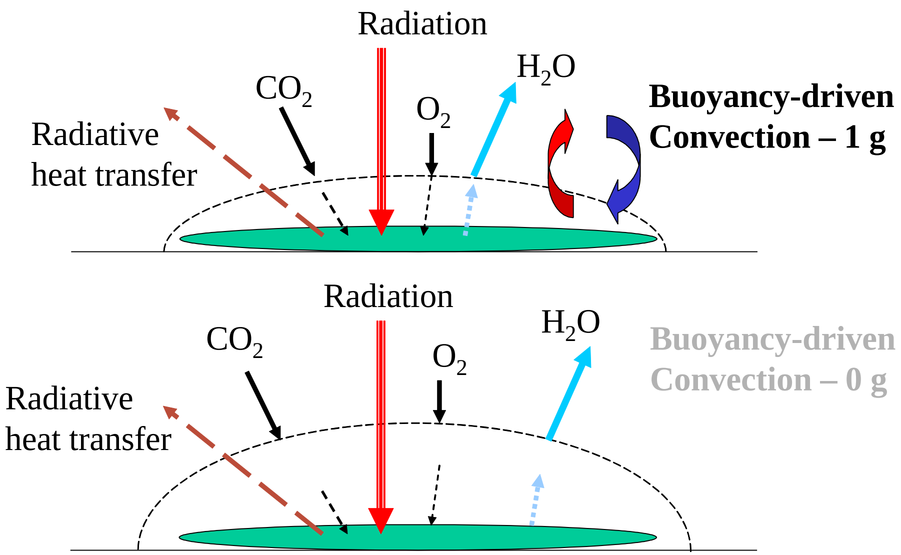
- Scale – Expand from Experimental to Production
  - 300 g/d = daily: 50 g salad for Crew of 6
  - 1 m^2 Planting area
- Performance criteria:
  - Productivity – maximize
  - Consistency – robust, repeatable
  - Crew Time – minimal
- Spacecraft
  - Cabin air – CO_2, VOCs
  - Limited Power & Volume
  - Microgravity Effects
  - Water load to ECLSS

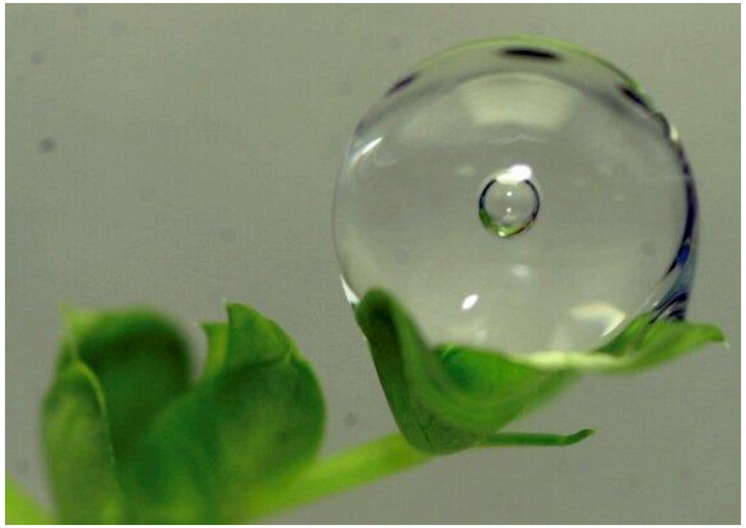


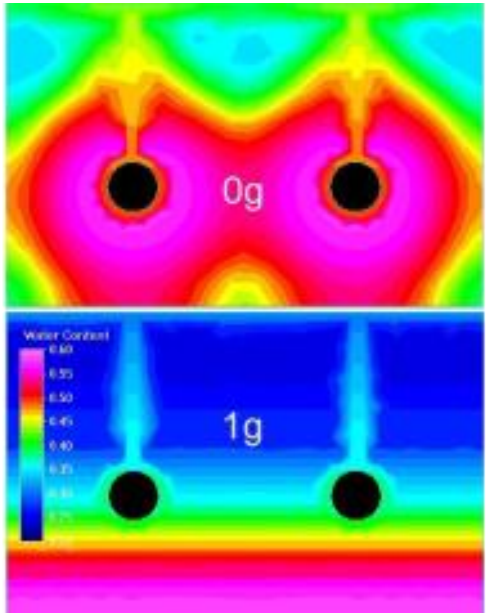
Nakamura, Monje & Bugbee AAIA 2013

Space-Flight Environment

The absence of gravity induces a number of physical effects that alter the microenvironment surrounding plants and their organs.
These effects include increased boundary layers surrounding plant organs and the absence of convective mixing of atmospheric gases. In addition, altered behavior of liquids and gases is responsible for phase separation and for dominance of capillary forces in the absence of gravitational forces.







Passive

Plant Growth Systems in Space

- **Plant Growth Systems in Space**
  - **Salyut Space Stations**
    - Oasis Series
    - Vazon
    - Malachite
    - Biogravistat/Magnetobiostat
    - Svetoblok
    - Phyton Series
  - **Mir**
    - SVET
    - SVET-GEMS
    - Vazon
    - Svetoblok
    - Astroculture (ASC)
  - **Space Shuttle**
    - Plant Growth Unit (PGU)
    - Plant Growth Facility (PGF)
    - Astroculture (ASC)
    - Plant Generic Bioprocessing Apparatus (PGBA)
  - **International Space Station (ISS)**
    - Advanced Astroculture (ADVASC)
    - Biomass Production System (BPS)
    - Lada
    - European Modular Cultivation System (EMCS)
    - Plant Experiment Unit (PEU)
    - Advanced Biological Research System (ABRS)
    - VEGGIE

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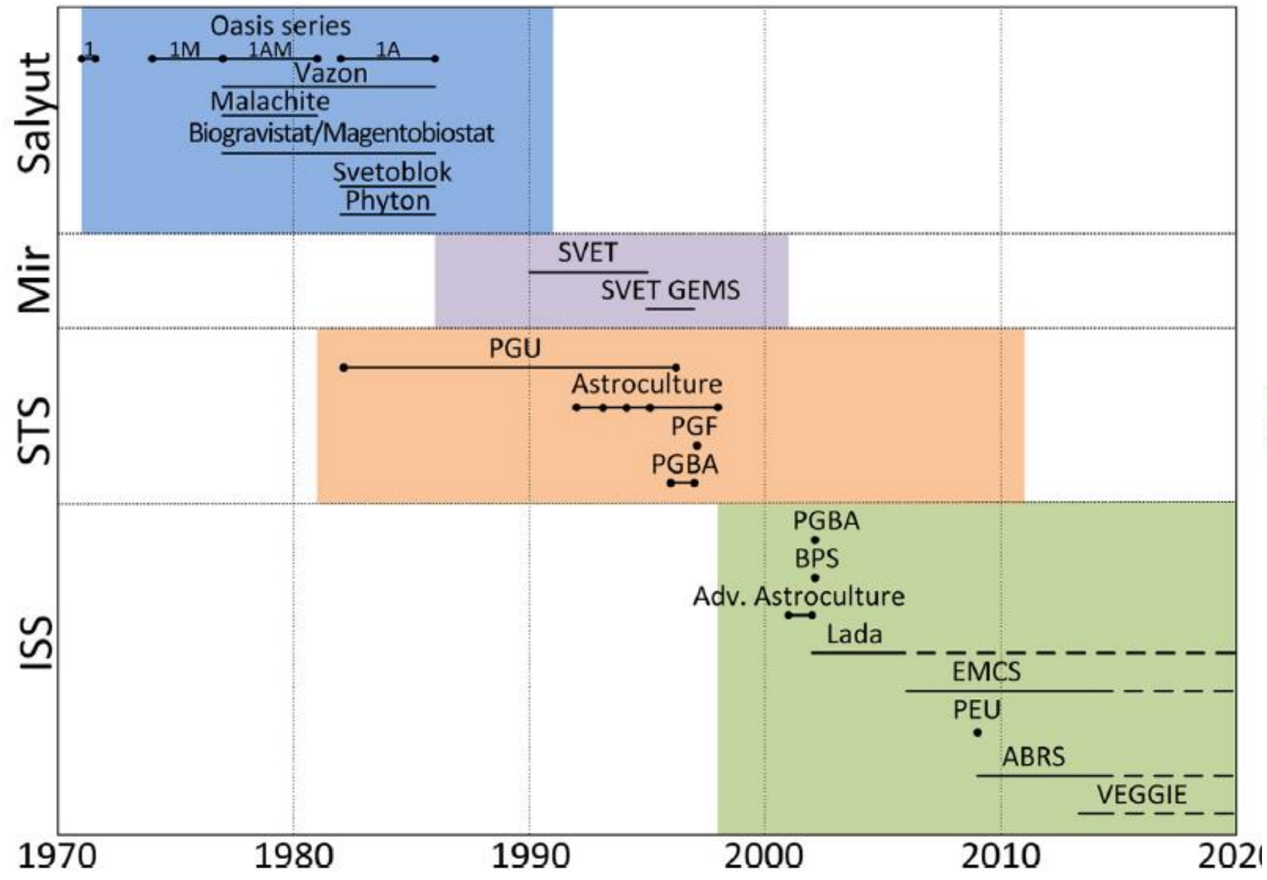
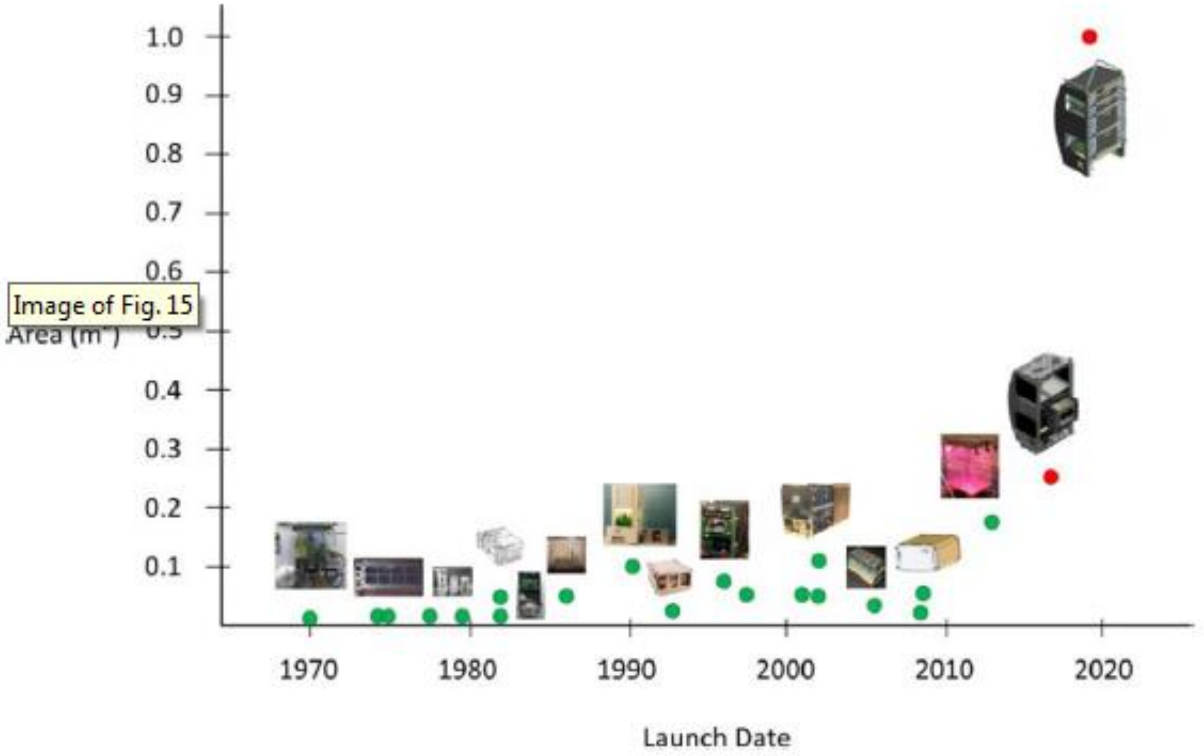
Passive

Plant Growth Systems in Space





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Passive

Plant Growth Systems in Space

Table 2
Detailed information on the nutrient delivery systems used in flown plant growth chambers.

	Nutrient delivery subsystem
Oasis 1	Two compartment system (water and ion exchange resin)
Oasis 1M	Fibrous ion exchange medium
Oasis 1AM	Cloth ion exchange medium
Oasis 1A	Included root zone aeration system
Vazon	Cloth sack filled with ion exchange resin
Malachite	Ion exchange resin, water supply
Biogravistat/ Magnetobiostat	n.a.
Svetoblok	Agar based, later also used other media
Phyton	1.5% agar nutrient medium
SVET	Polyvinyl formal foam surrounded perforated tubing wrapped in a wick within zeolite based substrate enriched with nutrients
SVET-GEMS	Similar to SVET but with additional sensors
PGU	Passive system capable of containing varied substrates/materials
PGF	Passive system capable of containing varied substrates/materials
ASC	Porous tubes in matrix
PGBA	Agar, soil or growth substrate in gas permeable polypropylene bags with option to connect bags to water supply
ADVASC	Porous tubes in matrix
BPS	Porous tubes in matrix
Lada	Perforated tubing wrapped in a wick within a matrix
EMCS	Water reservoir providing water to experiment unique nutrient delivery equipment
PEU	Rock wool fed by integrated water line
ABRS	Experiment specific
VEGGIE	Passive NDS, rooting pillows, manual water and nutrient supply

Table 4
Detailed information on the atmosphere management systems used in flown plant growth chambers.

	Temperature and humidity control	CO_2 control	Trace gas control	Additional information
Oasis 1	no	no	no	Closed vegetation boxes.
Oasis 1M	no	no	no	Closed vegetation boxes.
Oasis 1AM	no	no	no	Closed vegetation boxes.
Oasis 1A	n.a.	n.a.	n.a.	Ventilation fan to remove excessive heat generated by lamps. Plants grew in cabin atmosphere.
Vazon	n.a.	n.a.	n.a.	Plants grew in cabin atmosphere.
Malachite	no	no	no	Closed vegetation box.
Biogravistat/ Magnetobiostat	no	no	no	Closed vegetation box.
Svetoblok	no	no	no	Closed vegetation box. Sterile environment.
Phyton	partly	no	no	Ventilation including bacterial filters.
SVET	partly	no	no	Ventilation fan to remove excessive heat generated by lamps. Oxygen supply to the root module. Environmental condition sensor package including temperature, humidity, substrate moisture.
SVET-GEMS	only temperature	no	no	Two separate air streams (one for plants one for cooling lamps). Large environmental sensor package, including: photosynthesis and transpiration measurements, CO_2 and O_2 sensors, temperature, humidity, substrate moisture.
PGU	only temperature	no	no	Could be equipped with an air exchange system, when sacrificing 1/5 of the cultivation area.
PGF	yes	yes	yes	Ethylene filter.
ASC	yes[a]	yes[b]	yes[c]	Ethylene scrubber unit to fully oxidize ethylene to CO_2 and water.
PGBA	yes	yes	yes	Ventilation with cabin air. Absorption beds to keep CO_2 level within requirements. Same ethylene scrubber technology as ASC.
ADVASC	yes	yes	yes	Same equipment as in ASC.
BPS	yes	yes	yes	Injection of pure CO_2. Ethylene scrubber and particulate filter. Photosynthesis and transpiration measurements.
Lada	yes	no	no	
EMCS	yes	yes	yes	Gas supply unit, pressure control unit, ethylene removal unit.
PEU	yes	yes	no	
ABRS	yes	yes	yes	VOC removal with potassium permanganate ($KMnO_4$).
VEGGIE	only temperature	no	no	Cabin air to control temperature and CO_2 level.

[a] First integrated for ASC-3 mission.
[b] First integrated for ASC-6 mission.

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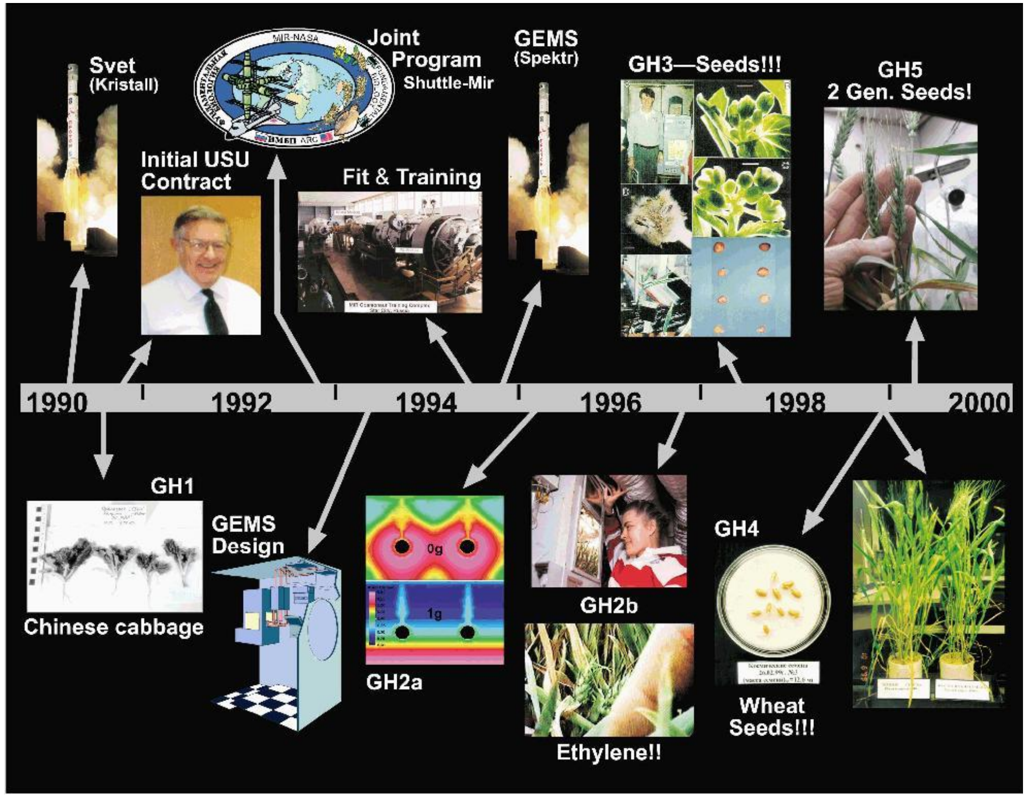
Passive

Plant Growth Systems in Space



"A single experiment in space, carried out by a given team, may well produce results that are in themselves only marginally valuable. Follow-up studies can be most helpful."

F.B. Salisbury - 2003

Researchers Achieve Breakthrough by Growing Plants from "Seed to Seed" in Space

Researchers led by NASA-supported investigator Mary E. Musgrave have succeeded in growing plants through a full life cycle—from seed to seed—in space, demonstrating that gravity is not required for plants to reproduce. The experiments were conducted aboard the Russian space station Mir by the first "farmer in space," astronaut C. Michael Foale.

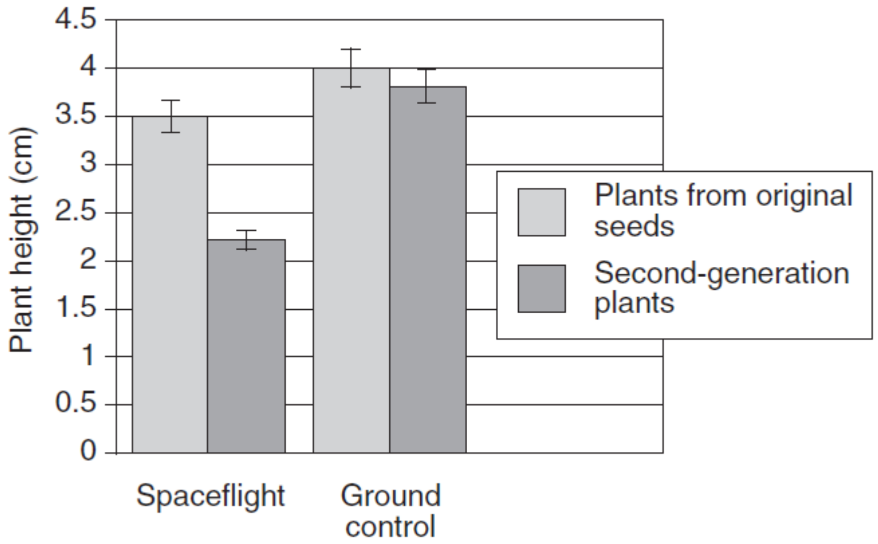


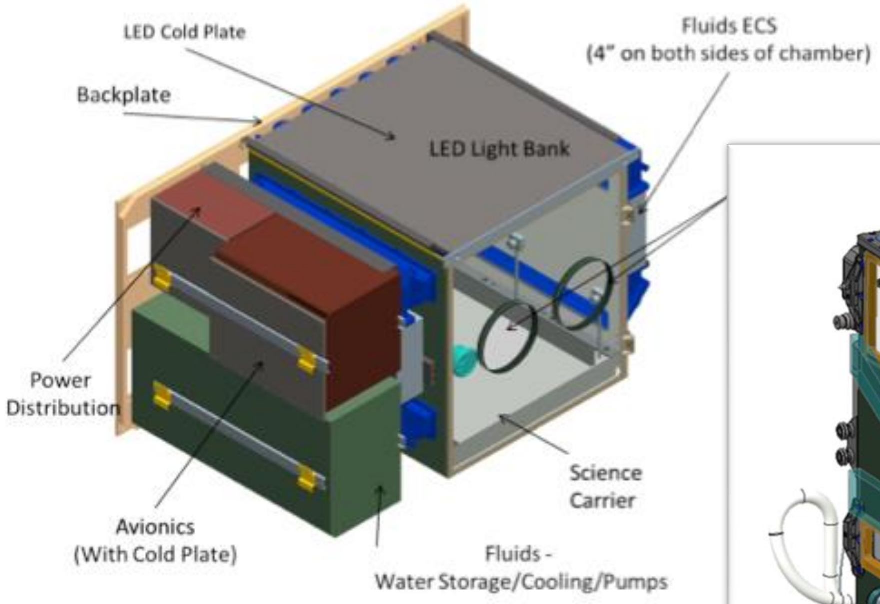
Table 5. Summary of experiments on early reproductive development in *Arabidopsis thaliana* (Chromex-03, -04, and -05) on STS-54, STS-51 and STS-68

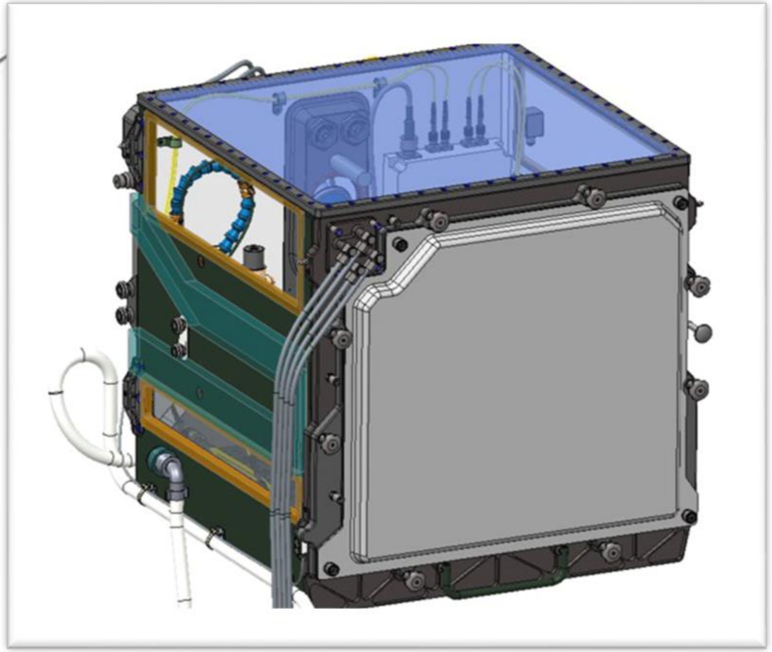
Experiment	Duration	Chamber configuration	Early reproduction	Pollination/seeds
Chromex-03	6 days	Sealed chambers	Pollen and embryo sac aborted	Pollen non-viable[a]
Chromex-04	10 days	Sealed chambers + CO_2	Androecium and gynoecium normal	No pollen transfer[b]
Chromex-05	11 days	Continuous air flow	Androecium and gynoecium normal	Normal[c]

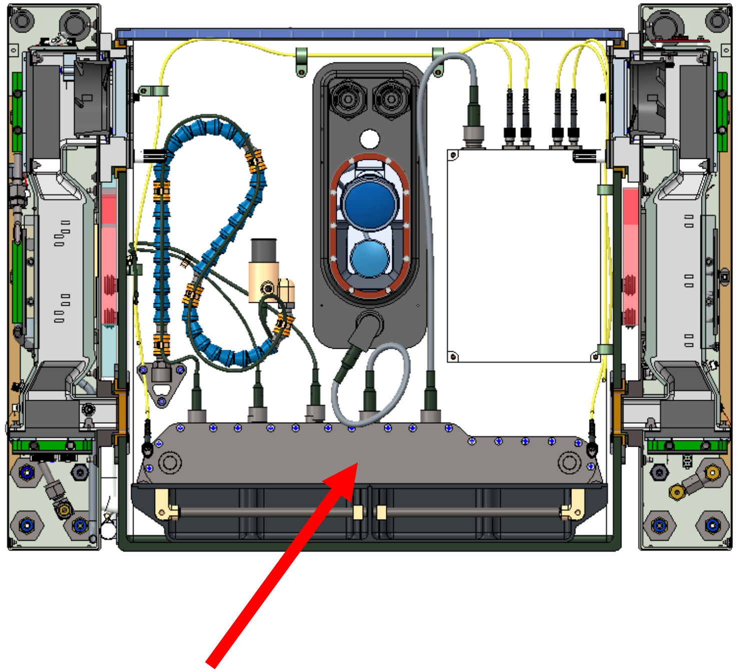
[a] As determined post-flight by fluorescein diacetate staining. Refer to Kuang *et al.* (1995) for complete details on reproductive development in these plants.
[b] As determined post-flight by scanning and transmission electron microscopy. Refer to Kuang *et al.* (1996a) for complete details on reproductive development in these plants.
[c] Refer to Kuang *et al.* (1996b) and Musgrave *et al.* (1997) for details.

APH Science Carrier

- The Science Carrier (SC) is an instrumented 0.2 m^2 root module within the Growth Chamber.

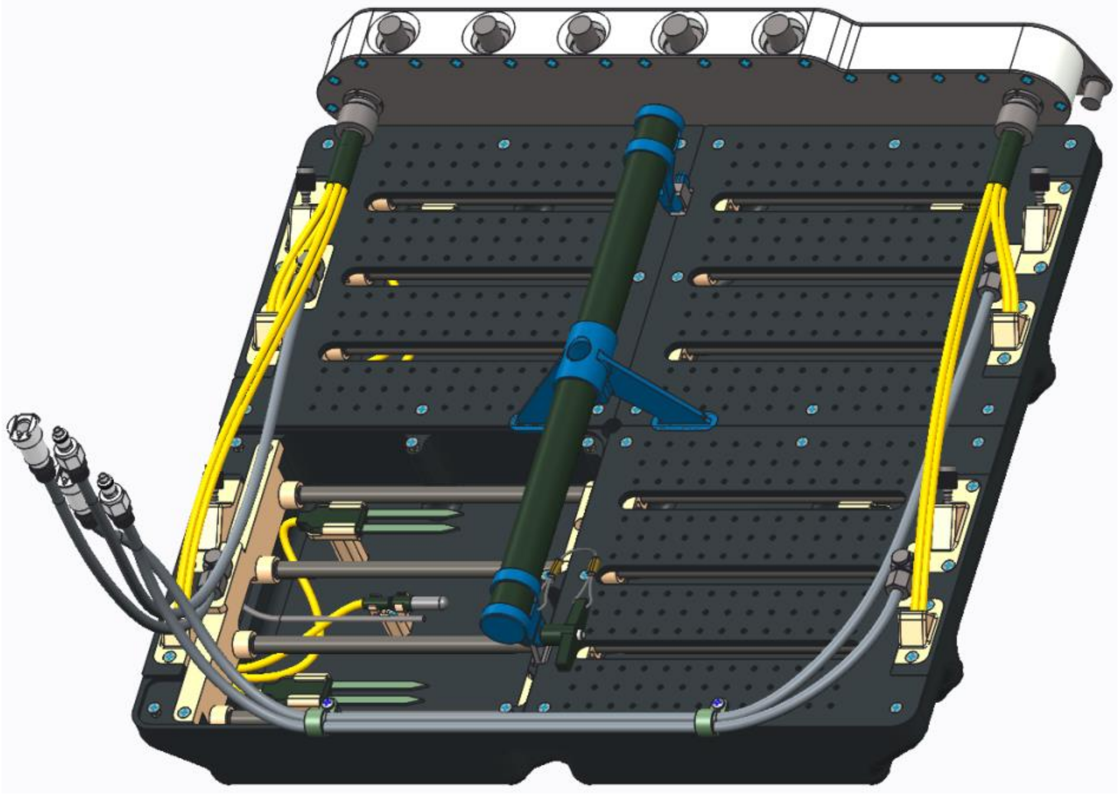






APH Science Carrier

APH Science Carrier (SC)

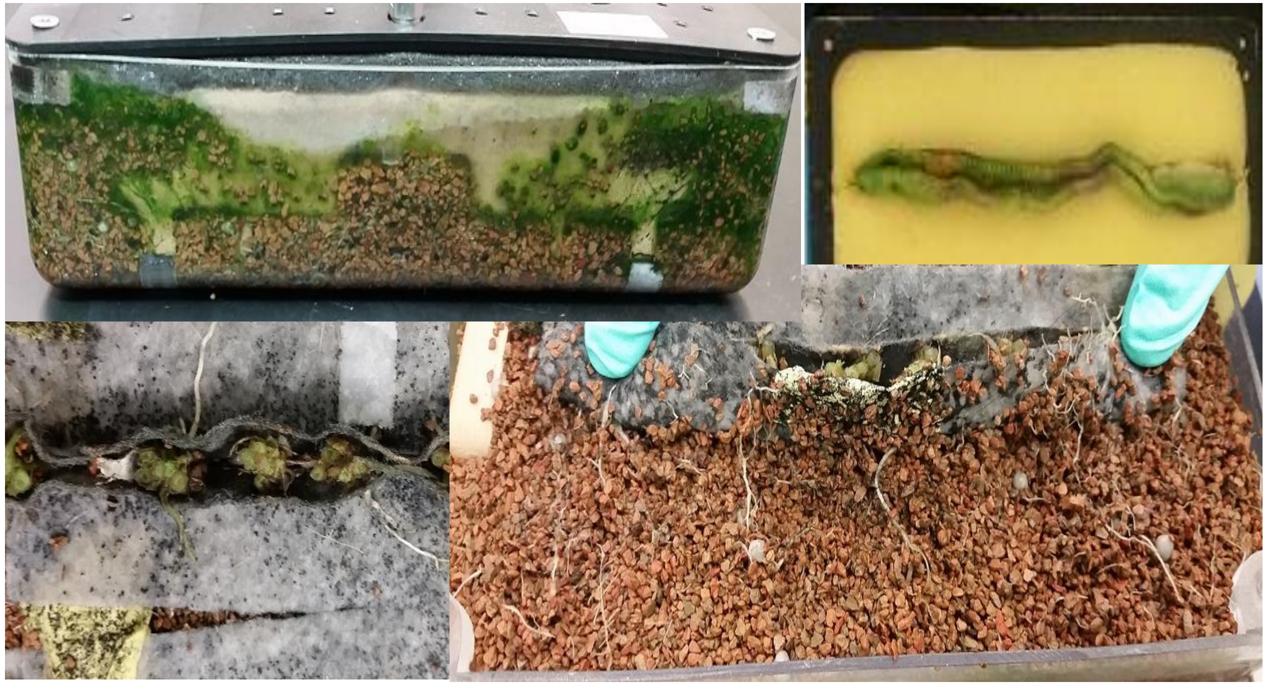


- The SC root tray is divided into four quadrants. Each quadrant contains the growth media, fertilizer, and water. Water is supplied from APH through four porous tubes connected to a manifold.

Scaling Food Production Systems: Media Mass

Growth Media - problems

- Bulky – containment, aeration
- Multiple plantings – loss of productivity
- Fungal growth – plant & crew health



Salads – 30 d cycles
5cm deep modules
12 plantings/year

Media		Advanced Plant Habitat	Salad Machine	
	Area	0.2	1.0	m^2
Granular	Mass	6	30	kg/planting
1 year		72	360	kg media

Future Work – Exploration

- Optimize to prevent secondary effects of microgravity
- Provide Nutrients – Obtain from waste
- Reduce Consumables – Media must be reusable